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ABSTRACT

This paper focuses on the financial effectiveness of vibration mitigation measures in urban environments. It highlights the comparison among new methods using subgrade stiffening, open trenches, and soft-filled barriers for mitigating ground-borne vibrations, which are often observed along railway corridors. The excessive ground-borne vibration can cause structural damage of safety-critical track components and surrounding infrastructures. In many cases, the neighboring assets such as buildings, tunnels, and so on are affected by railway ground-borne vibrations. This level of vibration can sometimes cause not only nuisance but also structural damages to the assets. Therefore, this paper is devoted to systems thinking approach and life cycle assessment in resolving railway crossing vibration problems. The life cycle of fifty years has been selected, as it is coincide with the majority of common design life for railway tracks catering freights, heavy haul trains, mixed traffics and heavy suburban trains globally. Based on assumptions commonly derived in rail

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industry, the life cycle analyses under variant extreme weather conditions reveal that using subgrade stiffening method seems to be the most efficient method for mitigating vibroacoustic problems, whilst the noise barrier seems to be the worst counterpart in railway corridor.

1 INTRODUCTION

One of the greatest challenges in operating railway business across a large network is the issue involving noise and vibration. Especially in urban railway network, noise and vibration is a pressing issue needed for a sustainable systems-based solution. Over the past decades, many mitigation methodologies have been developed but their relative effectiveness remains unknown considering the effort (cost, time, maintainability) needed to place or install them. The first thing that needs to be taken into consideration is the physics behind such phenomena. Depending on the type of noise and vibration generated, there is often a physical difficulty and practical constraint to control the noise and vibration waves, which require appropriate control mechanisms that are practical and suitable [1-6]. In addition, an urban railway network usually spans across hundreds or even thousands of kilometres long. Any implementation to mitigate railway noise and vibration are often very expensive to be built along all the railway line. In order to identify an optimal methodology, a comparison between their effectiveness and the need for maintenance in order to predict the whole-of-life cost is very necessary for the rail industry to implement such solutions [7-10]. In practice, the method of mitigation relies on the source of noise and vibration that is being resolved; however, the perception of noise is derivate from an interaction between different sections of the track and a single solution may not be as effective [11-14].

Major source of railway noise and vibration stems from the wheel/rail interface that generates nuisances such as rolling noise, impact noise, curve squeal, flanging noise, ground-borne and structural borne vibrations [1, 15, 16]. The amount of noise generated by this source is highly connected with other problems that the railway track may experience such as track degradation, differential settlement near bridges, loosen and pulverised ballast, and others. It is important to note that the secondary major source of disturbance is derived from the ground conditions. The dynamic loading condition transmitting from the rails to the ground foundation produces a great amount of energy and affects the surrounding areas of the track in the form of vibration, which can compromise the people living around and the constructions that could collapse under such disturbances. The amplitude of vibration depends on many factors such as the constituent materials of substructure of the railway and their ability to absorb impacts and constitute the ability to damp out due its physical properties [17-19]. The problems around rolling noise and its associated groundborne vibration have motivated this study. This paper presents the relatively new mitigation methodologies for groundborne vibration in railway corridor. Those are subgrade stiffening and open trench with soft-filled barrier. This paper is the first to highlight the life cycle evaluation of such the methodologies in terms of cost and resilience. The resilience of the methodologies is evaluated by the evaluation of robustness of each method exposed to extreme climate condition. In this study, the extreme climate condition includes only flash flood. This is because the mitigation methods in this study are an geotechnical or ground improvement method, which is relatively more sensitive to pore moisture content or ground water level [20-24]. The insight into the life cycle costs and resilience will help rail engineers and managers to sustainably improve the railway noise and vibration management within the rail environment.

2 GROUNDBORNE VIBRATION AND ITS MITIGATION

2.1 Groundborne Vibration

Groundborne vibration is often generated by a different mechanism from the one at wheel/rail interface. Groundborne vibration can be perceived mostly in terms of vibration, although it may re-generate secondary effects on building acoustics (e.g. low-frequency rumbling noise, frictional noise from components rubbing, etc.). In many cases, the groundborne vibration can cause damage to the buildings or infrastructure, and it is a constant disturbance for living areas near by the track. The assessment of vibration results in an analogy of noise effect, determining the total effect of the surrounding living areas within a period. The vibration propagated through the ground can be in low frequencies (below 10 Hz) in the case of surface propagation or, in the case of groundbourne, in higher frequencies, around 30 to 250 Hz [25]. The energy transmitted depends on the properties of damping system, materials used and how the force is distributed along the structure. The human response to vibration is influenced by the acceleration of the waves and it is important to outline that the perception of noise and vibration is higher indoors, where the building is highly affected by the increase of energy.

2.2 Subgrade Stiffening

In many locations, deep excavation is impossible and track space/clearance is very limited due existing corridors around the railway track. Therefore, subgrade stiffening is a methodology where the soil under or close to the track is stiffened to modify the ground layer structure as shown in Fig. 1. The modification can be the heavy compaction or cement stabilization of the soil. The later approach is more common and practical to railway network as the cement-stabilised soil is relatively more durable, in comparison with compacted soil.

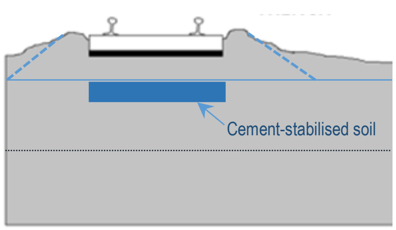

Fig. 1 – Subgrade stiffening.

Table 1 - Cost Assumptions for life cycle analysis of subgrade stiffening.

Mitigation Measures (per km)	Open Trench with Soft-filled Barrier		
	Baseline (Untreated)		
	Control Case	Adverse climate	Carbon Footprint
Subgrade preparation			
£1,028,000 initial cost	£1,100 cost per month and maintenance every 25 years	£1,700 cost per month and maintenance every 15 years	No substantial value from natural geomaterial
Subgrade stiffening by cement-stabilised soil			
£1,028,000 initial cost £ 50,000 for cement-stabilised soil	£1,600 cost per month and maintenance every 25 years	£2,500 cost per month and maintenance every 5 years	Embedded material CO_2e of cement-stabilised soil: 15 CO_2e kg/m^3 (cross section of subgrade is 0.625 m^2)

Using this approach, the modal propagation regime can be changed and there is a vibration reduction at low frequency range. As the methodology consists uniquely in stiffening the soil, the cost generated is the special machinery used to compact and the cost of cement-stabilised soil. The CO_2 footprint is associated with the fuel burnt during the process and the embedded carbon in the material. Although the use of the machinery is a long process, the emission of CO_2 by the fuel is low compared with the carbon emission from the materials used as shown in Table 1. The adverse climate (e.g. flooding) can undermine the soil condition and induce cracking of stiffened subgrade or soil-cement. This problem can also be observed in road flexible pavement under soft soil condition.

2.3 Open trench with soft-filled barriers

The use of trenches with soft-filled barriers, as shown in Fig. 2, are a great mechanism to attenuate the vibrations generated by the track, especially for the low frequencies [1]. To attenuate ground vibration, it is necessary to build deep trench that is somewhat impractical. This deep excavation requires soil stabilization structure to maintain the geotechnical integrity. The soft-filled barrier such as foamed material can be used to fill the void and to provide the stability to surrounding soil and to isolate the vibration from the railway track to surrounding infrastructure. For noise mitigation purposes, the depth of 4 meters was adopted and it can decrease in half the height of the wavelength. The foam is chosen to fill in and stabilise the trench. As presented in Table 2, the costs for the methodology include, in both cases, the excavation and soil stabilisation along the track. The trenches also need contention of the soil around and protection to avoid soil loosening.

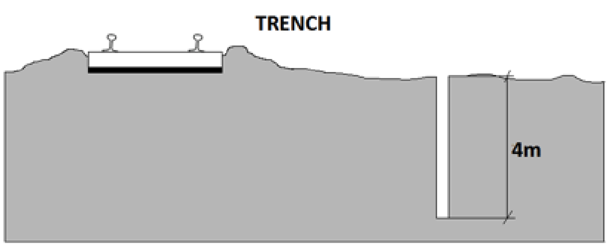

Fig. 2 – Open trench for soft-filled barriers.

Table 2 - Cost Assumptions for life cycle analysis of open trenches.

	Open Trench with Soft-filled Barrier		
Mitigation Measures	Baseline (Untreated)		
(per km)	Control Case	Adverse climate	Carbon Footprint
Trenches			
£ 1,245,626.70 initial cost	£1,100 cost per month and maintenance every 25 years	£1,700 cost per month and maintenance every 15 years	No substantial value from geomaterial
Trenches with foam filler			
£ 1,245,626.70 initial cost £ 100,000 for foam filler	£1,600 cost per month and maintenance every 25 years	£2,500 cost per month and maintenance every 5 years (broken foam)	Embedded material CO_2e of foam: 4.2 CO_2e kg/kg (density 62 kg/m^3)

Under climate adverse condition, the foam can be damaged or broken from hydraulic pressure and so on. This can cause unplanned maintenance activity to inspect and replace the foam filler more frequently. It is important to note that the discount rate used for life cycle cost analyses is 5%. The service life of 50 years has been considered in this study.

3 LIFE CYCLE ASSESSMENT

Based on Fig. 3, the outcome of the analysis shows that the subgrade stiffening will be relatively less expensive at the end of the life cycle, since the annual cost for maintenance is lower compared to the initial cost of the method. In the case of extreme climate condition (flooding), the subgrade stiffening has a lower cost with the same reduction of noise. Fig. 4 reveals that the carbon emission of cement-stabilised soil is much more significant, compared to light foam-based material. The cement-stabilised soil tends to induce the worse environmental impact.

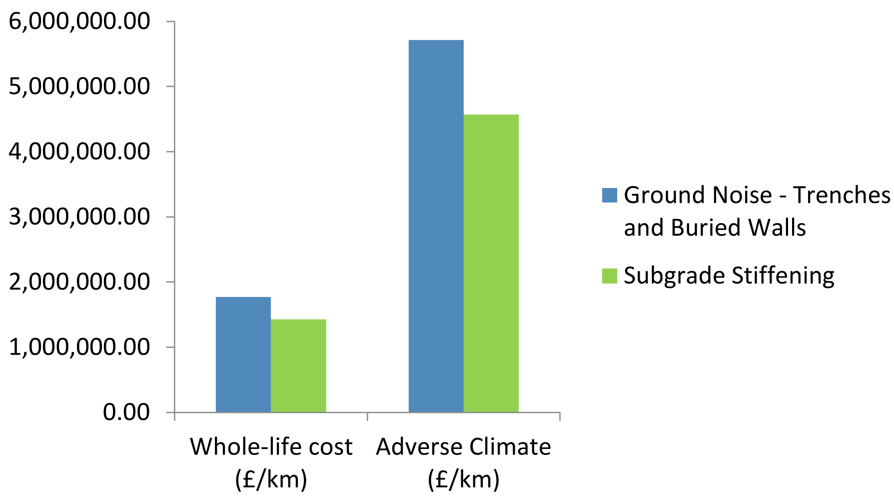

Fig. 3 – Comparison of life cycle costs (at 5% discount rate).

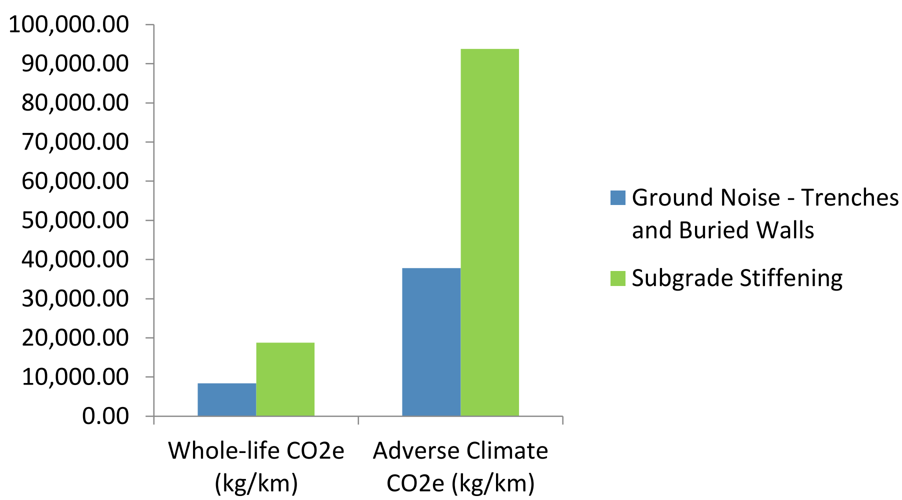

Fig. 4 – Comparison of life cycle CO_2e.

4 CONCLUSIONS

The larger part of investment is usually driven for the maintenance of the track systems. This investment helps on the longevity of the railway track, but it also leads to a perceptive reduction in terms of noise and vibration. However, only the maintenance is not enough to fully control those outcomes, resulting in the necessity of creating new methodologies to have a better reduction in noise and vibration. In this study, some of the key methodologies were analysed considering its life cycle, which is a more suitable parameter for evaluating the available technologies within the industry and can be for great use to choose the optimal and most suitable solution for the railway vibration and noise mitigation methodology.

The life cycle evaluation embraces both the cost and the environmental impact generated by different modern methodologies of reduction in noise and vibration of groundborne vibration using open trench and subgrade stiffening. The cost matter usually is the one that caught more attention of railway organisations; however, more recently the necessity to reduce the CO_2 carbon footprint has become a great issue. The life cycle analysis reveals that the subgrade stiffening is the more economical whilst the open trench is the more environment-friendly. The impacts and values of noise and vibration mitigations can vary from urban area to rural network since in the first instance the noise impact affect the citizens' everyday life in urban areas and a large-scale urban infrastructure, whilst, for rural rail network, the disturbance are mainly affecting the nearby ecosystems, their accommodated species, and pasture growth/production.

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